

Towards extracting the best possible results from NO ν A

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Abstract The NuMI Off-Axis ν_e Appearance (NO ν A) is the currently running leading long-baseline neutrino oscillation experiment, whose main physics goal is to explore the current issues in the neutrino sector, such as determination of the neutrino mass ordering, resolution of the octant of the atmospheric mixing angle, and to constrain the Dirac-type CP violating phase δ_{CP} . In this paper, we would like to investigate whether it is possible to extract the best possible results from NO ν A with a shorter time span than its scheduled run period by analyzing its capability to discriminate the degeneracy among various neutrino oscillation parameters within 4 years of run time, with 2 years in each neutrino and antineutrino modes. Further, we study the same by adding the data from the T2K experiment for a total of 5 years run with 3.5 years in neutrino mode and 1.5 years in antineutrino mode. We find that NO ν A (2 + 2) has a better oscillation parameter degeneracy discrimination capability compared to its scheduled run period for 4 years, i.e., NO ν A (3 + 1).

1 Introduction

The results from various neutrino oscillation experiments [1–7] confirm that neutrino flavors mix with each other and neutrinos do possess tiny but non-zero masses. This neutrino mixing can be described by a unitary matrix, the so-called Pontecorvo–Maki–Nagakawa–Sakata (PMNS) matrix, which is parameterized by three mixing angles, often referred to as the solar mixing angle (θ_{12}), the atmospheric mixing angle (θ_{23}), and the reactor mixing angle (θ_{13}); and a Dirac-type CP violating phase (δ_{CP}) [8, 9]. The probability of neutrino oscillation depends on these parameters as well as on two mass squared differences, namely, the solar mass squared difference (Δm_{21}^2), and the atmospheric mass squared difference (Δm_{31}^2). All these parameters are determined through various neutrino experiments except the Dirac CP phase. However, we do not know the mass ordering of the

neutrinos, i.e., the sign of Δm_{31}^2 and this leaves us with two choices: normal ordering/hierarchy (NH) with $\Delta m_{31}^2 > 0$ and inverted ordering/hierarchy with $\Delta m_{31}^2 < 0$. Furthermore, a recent experimental result from MINOS [10] shows that θ_{23} is non-maximal. Therefore, the octant of the mixing angle θ_{23} remains unknown, i.e., it lies in the lower octant (LO) i.e., $\theta_{23} < 45^\circ$ or in the higher octant (HO) with $\theta_{23} > 45^\circ$. There are many neutrino oscillation experiments which are intended to determine these unknowns. Among all these experiments, NO ν A is one of the new generation accelerator based long-baseline experiments which aims to determine most of these unknown parameters.

The NO ν A [11–14] experiment is currently running long-baseline neutrino oscillation experiment, which uses an upgraded NuMI beam power of 0.7 MW at Fermilab. It has a 14 kton totally active scintillator detector (TASD) placed 0.8° off-axis from the NuMI beam near the Ash River, situated 810 km far away from Fermilab. It also has a 0.3 kton near detector located at the Fermilab site to monitor the un-oscillated neutrino or antineutrino flux. This experiment is designed to observe both $\nu_e(\bar{\nu}_e)$ appearance events and $\nu_\mu(\bar{\nu}_\mu)$ disappearance events. The main physics goals of this experiment are:

- Appearance events: To determine the value of θ_{13} , determination of the octant of θ_{23} , the mass ordering, and constrain the Dirac CP phase.
- Disappearance events: The precision measurement of atmospheric oscillation parameters, Δm_{23}^2 and θ_{23} .

The determination of these parameters by an oscillation experiment like NO ν A, which should mainly rely on the oscillation probability, is extremely difficult due to the parameter degeneracies, since various combinations of these parameters give the same probability. A lot of work has been done in the literature to resolve these degeneracies among oscillation parameters [15–17]. Moreover, there was a suggestion for the need of an early antineutrino run to get a first hint of the mass ordering in NO ν A [18]. There it has been

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shown that the sensitivity for the determination of mass hierarchy is above 2σ (i.e., $\chi^2 > 4$) only for δ_{CP} value around $\mp 90^\circ$ for true hierarchy and octant as NH-LO or HO-IH, where the scheduled run time, i.e., 3 yrs in ν mode + 0 yr in $\bar{\nu}$ mode, gives almost null sensitivity. The scheduled run period of NO ν A is for a total of 6 years with first 3 years in neutrino mode followed by the next 3 years in antineutrino mode. Therefore, it is of great importance to study the ability to discriminate the degeneracies between different oscillation parameters of this experiment within a minimal time span, since it leads to an early understanding of the neutrino oscillation parameter space. In this context, we investigate in this paper how to extract the best possible results from NO ν A with shortest time span by analyzing its physics potential and degeneracy discrimination capability for a total of 4 years of runs, with 2 years in each neutrino and antineutrino modes. We have shown that the (2 + 2) years of run will provide a much better sensitivity for the mass hierarchy determination in comparison to its scheduled run for 4 years, i.e., 3 years in neutrino mode followed by 1 year in antineutrino mode. Furthermore, we also studied the same by adding data from the T2K experiment for a total of 5 years run with 3.5 years in neutrino mode and 1.5 years in antineutrino mode.

The outline of this paper is as follows. In Sect. 2, we present the details of the simulation of T2K and NO ν A experiments that we have considered in this work. The neutrino oscillation parameter degeneracies are discussed in Sect. 3. Section 4 contains the discussion as regards the mass ordering and octant determination. Finally, we summarize our results in Sect. 5.

2 Simulation details

We simulate the neutrino oscillation events for T2K (Tokai-to Kamioka) as well as NO ν A experiments by using GLoBES package [19,20]. T2K is also a currently running off-axis long-baseline experiment, which has been designed to study the phenomenon of neutrino oscillation. It uses an upgraded beam power of 0.77 MW and has a water Cherenkov detector of mass 22.5 kton placed about 295 km away from Tokai. We simulate the T2K experiment [21–23] with an updated experimental description as given in [24]. As we mentioned earlier, the NO ν A experiment is an off-axis experiment with a baseline of 810 km, which uses a beam power of 0.7 MW and a detector with a mass of 14 kton. The experimental specifications of NO ν A are taken from [25] with the following characteristics:

Signal efficiency: 45 % for ν_e and $\bar{\nu}_e$ signal; 100 % ν_μ CC and $\bar{\nu}_\mu$ CC.

Background efficiency:

- (a) Mis-ID muons acceptance: 0.83 % for ν_μ CC, 0.22 % for $\bar{\nu}_\mu$ CC;

Table 1 The true values of oscillation parameters considered in the simulations are taken from [26]

$\sin^2 \theta_{12}$	0.32
Δm_{21}^2	$7.6 \times 10^{-5} \text{ eV}^2$
$\sin^2 2\theta_{13}$	0.1
Δm_{atm}^2	$2.4 \times 10^{-3} \text{ eV}^2$ for NH $-2.4 \times 10^{-3} \text{ eV}^2$ for IH
$\sin^2 \theta_{23}$	0.41 (LO), 0.59 (HO)
δ_{CP}	0°

- (b) NC background acceptance: 2 % for ν_μ NC, 3 % for $\bar{\nu}_\mu$ NC;

- (c) Intrinsic beam contamination: 26 % for ν_e , 18 % for $\bar{\nu}_e$,

and we consider 5 % uncertainty on signal normalization and 10 % on background normalization. The migration matrices for NC background smearing are taken from [25]. The true values of the oscillation parameters that we use in our simulation are listed in Table 1 [26].

3 Neutrino oscillation parameter degeneracies

The parameter degeneracies in neutrino oscillation sector are of mainly three types and they are: $(\delta_{CP}, \theta_{13})$, the sign of Δm_{31}^2 , and $(\theta_{23}, \pi/2 - \theta_{23})$. Recently, the reactor experiments such as Daya Bay [27,28], Double Chooz [29], and RENO [30] have precisely measured the value of the reactor mixing angle as $\sin^2 2\theta_{13} \approx 0.089 \pm 0.01$. Therefore, the eight-fold degeneracy is reduced to a four-fold degeneracy. Out of these degeneracies, the degeneracy in which θ_{23} cannot be distinguished from $(\pi/2 - \theta_{23})$ is called the octant degeneracy and the degeneracy in the sign of Δm_{31}^2 is called the hierarchy ambiguity. So far, we are left with four degeneracies and they can be represented as NH-HO, NH-LO, IH-HO and IH-LO, where NH/IH (HO/LO) stands for normal/inverted ordering (higher/lower octant). The resolution of these degeneracies is among the main challenges of the present and future long-baseline neutrino oscillation experiments, which are mainly looking for oscillation from $\nu_\mu (\bar{\nu}_\mu) \rightarrow \nu_e (\bar{\nu}_e)$. The expression for the oscillation probability, which is up to first order in $\sin \theta_{13}$ and $\alpha \equiv \Delta_{21}/\Delta_{31}$, is given by [31–33]

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) \approx & \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(\hat{A} - 1)\Delta}{(\hat{A} - 1)^2} \\
 & + \alpha \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \frac{\sin \hat{A} \Delta}{\hat{A}} \\
 & \times \frac{\sin(\hat{A} - 1)\Delta}{(\hat{A} - 1)} \cos(\Delta + \delta_{CP}), \quad (1)
 \end{aligned}$$

where $\Delta = \Delta_{31}L/4E$ with $\Delta_{ij} = m_i^2 - m_j^2$ and $\hat{A} = 2\sqrt{2}G_F n_e E / \Delta_{31}$, where G_F is the Fermi coupling constant

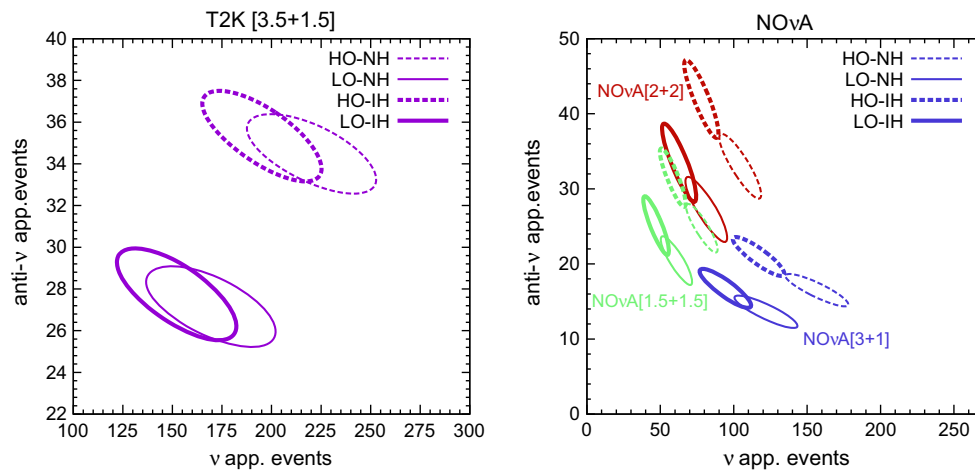


Fig. 1 Neutrino and antineutrino appearance events for the $\nu_\mu \rightarrow \nu_e$ versus $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channels by assuming both IH and NH and for lower and higher octants of θ_{23}

and n_e is the electron number density. For neutrinos, \hat{A} is positive for NH and negative for IH. For antineutrinos, \hat{A} and δ_{CP} reverse their sign, i.e., $\hat{A} \rightarrow -\hat{A}$ and $\delta_{CP} \rightarrow -\delta_{CP}$ for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$.

The best way to express the degeneracies without any mathematical expression is simply by using bi-events curves. The bi-events plots for various octant-hierarchy combinations of T2K and NOvA are depicted in Fig. 1, which are obtained by computing the $\nu(\bar{\nu})$ appearance events for the full range of δ_{CP} with a particular octant-hierarchy combination. From the plots, we can see that the ellipses for two hierarchies overlap with each other for both T2K and NOvA for the lower octant, which show that they have poor mass hierarchy discrimination capability. The overlap is minimal for higher octant in the case of NOvA, which shows that NOvA has a better degeneracy discrimination capability compared to T2K. However, the ellipses for HO and LO are very well separated and they have a good octant resolution capability. Moreover, NOvA (2 + 2) has a better capability to determine the octant of θ_{23} among all other combinations due to balanced ν and $\bar{\nu}$ runs.

4 Mass hierarchy and octant determination

In this section, we obtain the potential of the NOvA experiment to determine the mass hierarchy and octant of atmospheric mixing angle and discuss the role of mass hierarchy-octant parameter degeneracy in the determination of these parameters.

4.1 Mass hierarchy determination

For the mass hierarchy determination, we obtain the sensitivity by calculating the χ^2 with which one can rule out the

wrong hierarchy from the true hierarchy. We express this sensitivity as a function of the true value of δ_{CP} , since it can be seen from Eq. (1) that there exists a degeneracy between the hierarchy and δ_{CP} . Therefore, we simulate true events by taking NH (IH) as the true hierarchy and test events by taking IH (NH) as a test hierarchy for each true value of δ_{CP} . We obtain the χ^2 by using GLOBES and compare both event rates for the full range of δ_{CP} . We do a marginalization over all other parameters in order to get the minimum χ^2 . We also add a prior on $\sin^2 2\theta_{13}$. We obtain this χ^2 for various true values of $\sin^2 \theta_{23}$ (i.e., $\sin^2 \theta_{23} = 0.5$ for maximal mixing and $\sin^2 \theta_{23} = 0.41$ (0.59) for LO (HO), since the octant of the atmospheric mixing angle is unknown).

In Fig. 2, we plot the value of χ^2 , obtained for maximal mixing of atmospheric angle, as a function of δ_{CP} . The left panel corresponds to the true NH and the right panel is for the true IH. From these figures, we can see that the potential to determine the mass hierarchy for NOvA is above 2σ for less than half of the parameter space of δ_{CP} and it also depends on the neutrino mass ordering. The mass hierarchy sensitivity of NOvA (2 + 2) is lower (higher) than that of NOvA (3 + 1) for true NH (IH) and maximal mixing of atmospheric mixing angle. The sensitivity increases for a combined analysis of NOvA (2 + 2) and T2K (3.5 + 1.5) and has a 3σ significance in the case of the true NH. The mass hierarchy sensitivities for a non-maximal atmospheric mixing angle are presented in Fig. 3. We consider all possible combinations with $\sin^2 \theta_{23} = 0.41$ (0.59) for LO (HO) for different combinations of neutrino and antineutrino run modes like NOvA (2 + 1), NOvA (2 + 2), NOvA (3 + 0), and NOvA (3 + 1). From these plots, we can see that the value of χ^2 is always above 6 for all cases of NOvA (2 + 2), whereas for NOvA (3 + 1) the χ^2 value is below 6 ($\sim 2.4\sigma$) for the two combinations (NH-LO and IH-HO). Hence, NOvA (2 + 2) has a good mass hierarchy discrimination capability compared to

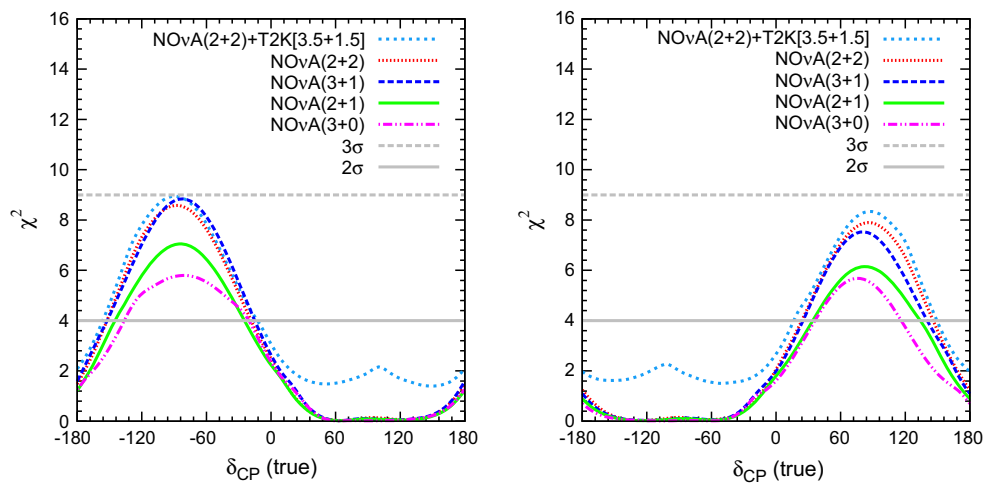


Fig. 2 The potential of determination of the mass hierarchy. NH is considered as the true hierarchy in the *left panel* and IH considered as the true hierarchy in *right panel*

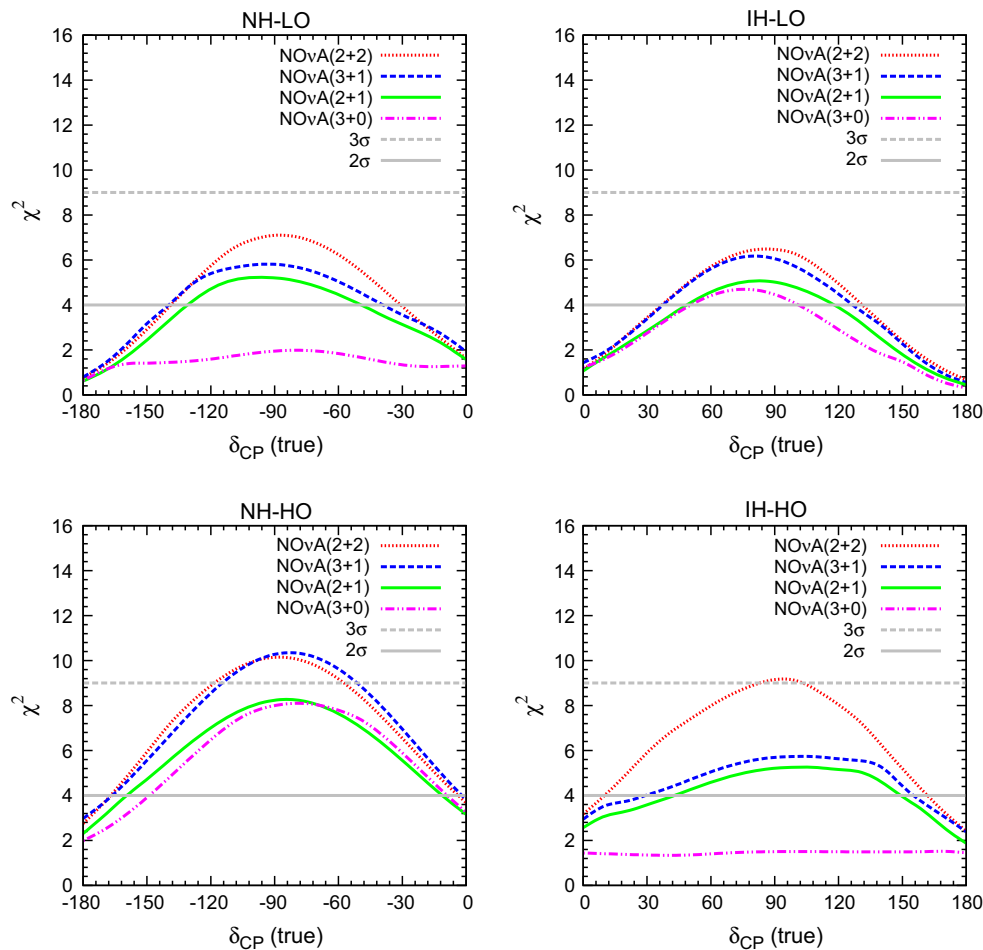


Fig. 3 The mass hierarchy sensitivities. The *top (bottom) panel* is for LO (HO), where we have used $\sin^2 \theta_{23} = 0.41$ (0.59) for LO (HO) and *left (right) panel* is for the true NH (IH)

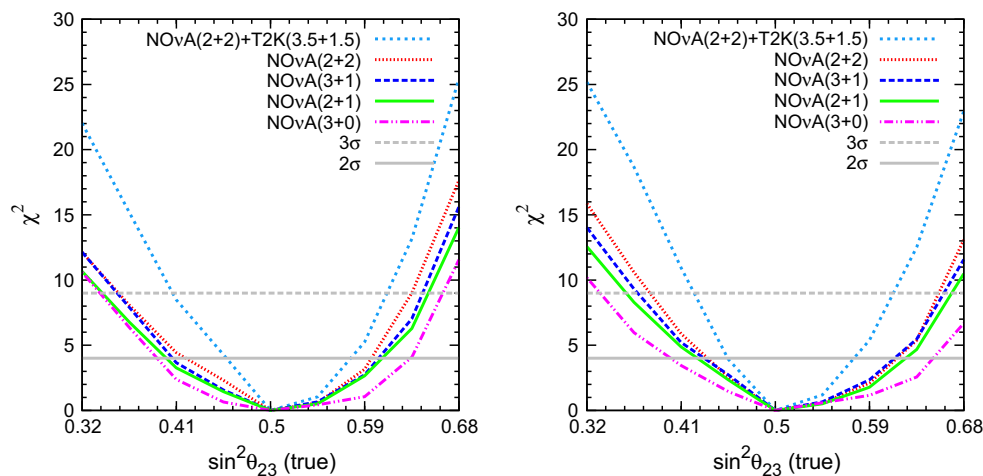


Fig. 4 The potential of octant resolution. NH is considered as true hierarchy in the *left panel* and IH considered as true hierarchy in *right panel*

the scheduled run of NOvA for 4 years. Thus, we can have early information as regards the nature of the mass ordering if NOvA runs in $(2\nu + 2\bar{\nu})$ mode rather than its scheduled run of $(3\nu + 1\bar{\nu})$ years. Furthermore, if nature would be kind enough in the sense that the real mass ordering is inverted in nature and θ_{23} lies in the higher octant, then the mass hierarchy can be determined with more than 2σ CL for values of δ_{CP} in the range $[0:180]^\circ$ with $(2\nu + 2\bar{\nu})$ years of run. Also if we compare the results of a 3 years of run, the sensitivity for the determination of mass hierarchy is better for the $(2 + 1)$ combination than the scheduled $(3 + 0)$ combination. This in turn implies that there would be better perspective if NOvA runs in antineutrino mode after completing 2 years of run in neutrino mode.

4.2 Octant of θ_{23} determination

The hint of a non-maximal atmospheric mixing angle observed by the MINOS Collaboration [10] is one of the recent subjects of interest in the neutrino oscillation sector. The deviation of θ_{23} from maximal ends up with two solutions; the so-called lower octant ($\sin^2 \theta_{23} < 0.5$) and higher octant ($\sin^2 \theta_{23} > 0.5$). For the determination of the resolution of the octant of θ_{23} , we obtain the minimum χ^2 with which one can distinguish the wrong octant from the true octant. Therefore, we simulate true events by taking LO (HO) as the true octant and test events by taking HO (LO) as test octant. In order to obtain the χ^2 , we compare the true events and test events for true values of $\sin^2 \theta_{23}$ in the range $[0.32:0.68]$. We marginalize over other parameters $\sin^2 2\theta_{13}$, Δm_{31}^2 within their 3σ range and δ_{CP} in its full range. We also add a prior on $\sin^2 2\theta_{13}$.

In Fig. 4, the obtained χ^2 is plotted as a function of $\sin^2 \theta_{23}$. The left panel corresponds to NH and the right panel corresponds to IH as true hierarchies. From the plots, it is clear that the potential to determine the octant of the atmo-

spheric angle is better for NOvA $(2 + 2)$, when compared with NOvA $(3 + 1)$. We can also see that a combined analysis of NOvA $(2 + 2)$ and T2K $(3.5 + 1.5)$ has good octant resolution sensitivity.

4.3 Correlation between θ_{23} and Δm_{32}^2

The discovery reach of the mass hierarchy and octant of atmospheric mixing angles are crucial because of the degeneracies between the oscillation parameters. Therefore, the resolution of these degeneracies is very important for a clear understanding of the neutrino mixing phenomenon.

In this section, we focus on the θ_{23} and Δm_{32}^2 degeneracy. First of all, we would like to see how the hierarchy ambiguity affects the $\sin^2 \theta_{23}$ – Δm_{32}^2 parameter space. Therefore, we simulate the true events for a maximal value of $\sin^2 \theta_{23}$ ($\sin^2 \theta_{23} = 0.5$) and test events for allowed values of $\sin^2 \theta_{23}$ ($[0.32:0.68]$) and Δm_{32}^2 ($[2.05:2.75] \times 10^{-3} \text{ eV}^2$). We obtain the χ^2 by comparing true events and test events. We also do marginalization for both $\sin^2 2\theta_{13}$ and δ_{CP} and add a prior on $\sin^2 2\theta_{13}$. In Fig. 5, the obtained χ^2 is plotted as a function of $\sin^2 \theta_{23}$ and Δm_{32}^2 . From the plots, we can see that there is small difference in the allowed parameter space for NH and IH. However, there is no difference in the allowed parameter space for $(2 + 2)$ and $(3 + 1)$ years of NOvA running as far as the determination of Δm_{32}^2 is concerned. We get similar results when we compare the parameter space for both NOvA $(2 + 2)$ and NOvA $(3 + 1)$ and, as expected, such parameter spaces are significantly reduced when compared with NOvA $(2 + 1)$ and NOvA $(3 + 0)$. It should also be noted from the figure that the parameter space is substantially reduced for a combined analysis of T2K and NOvA. Therefore, if we combine the $(2 + 2)$ years of NOvA results with $(3.5 + 1.5)$ T2K results, the significance of the atmospheric mass square determination will improve significantly.

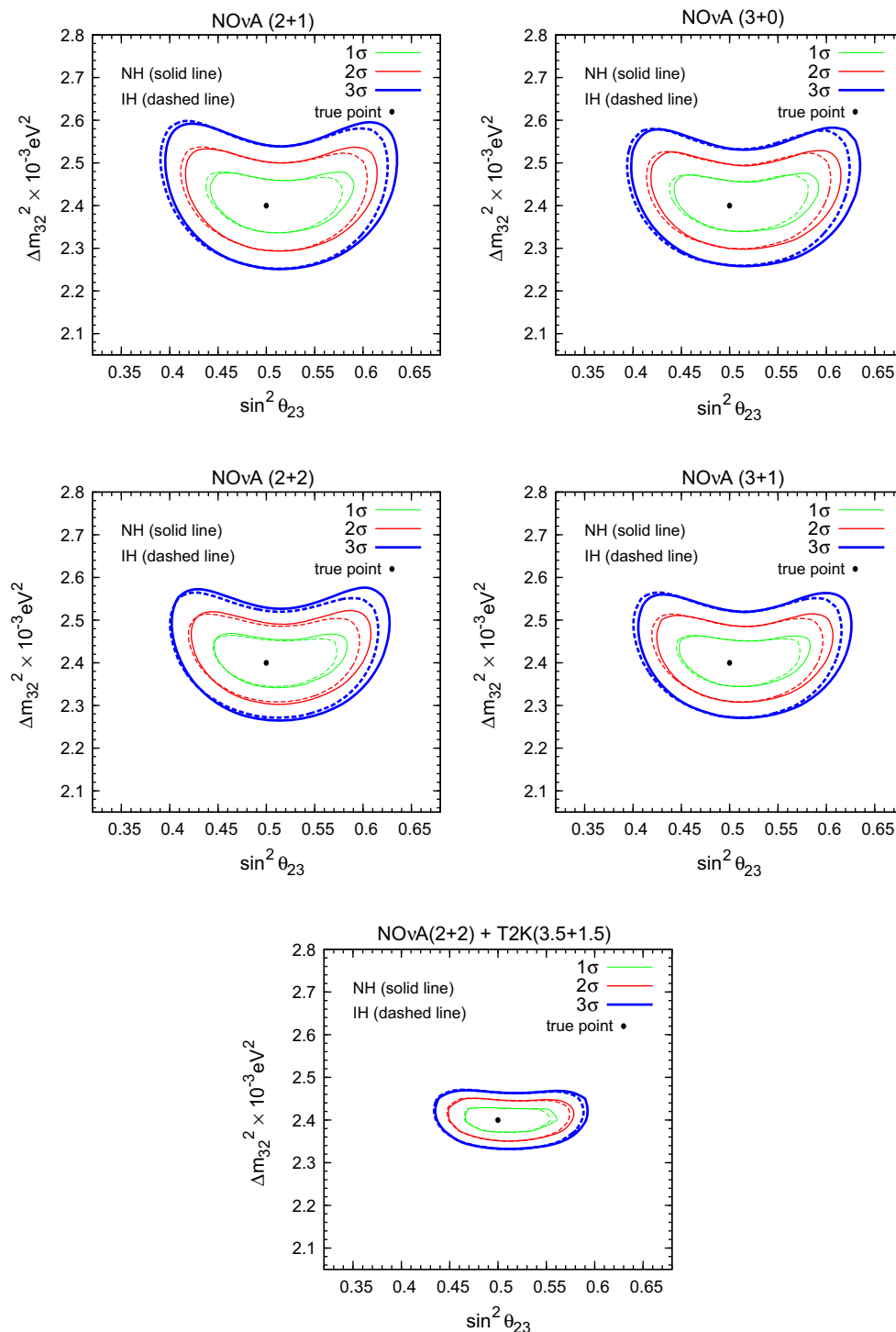


Fig. 5 The $\sin^2 \theta_{23}$ – Δm^2_{32} contour plots with true $\sin^2 \theta_{23} = 0.5$

We also obtain the $\sin^2 \theta_{23}$ – Δm^2_{32} parameter space for non-maximal mixing of the atmospheric mixing angle. We consider the deviation from maximal mixing with $\sin^2 \theta_{23} = 0.41(0.59)$ for the lower octant (higher octant). Figure 6 shows the $\sin^2 \theta_{23}$ – Δm^2_{32} parameter space for the NH–HO, NH–LO, IH–HO, IH–LO combinations. It is clear from the

figures that, in this case also, there is no significant difference between the allowed parameter space for (2 + 2) and (3 + 1) years of NOvA run period. Therefore, the expected results on θ_{23} and Δm^2_{32} degeneracy discrimination would not be deteriorated if NOvA switches to the antineutrino mode after completion of 2 years of neutrino run.

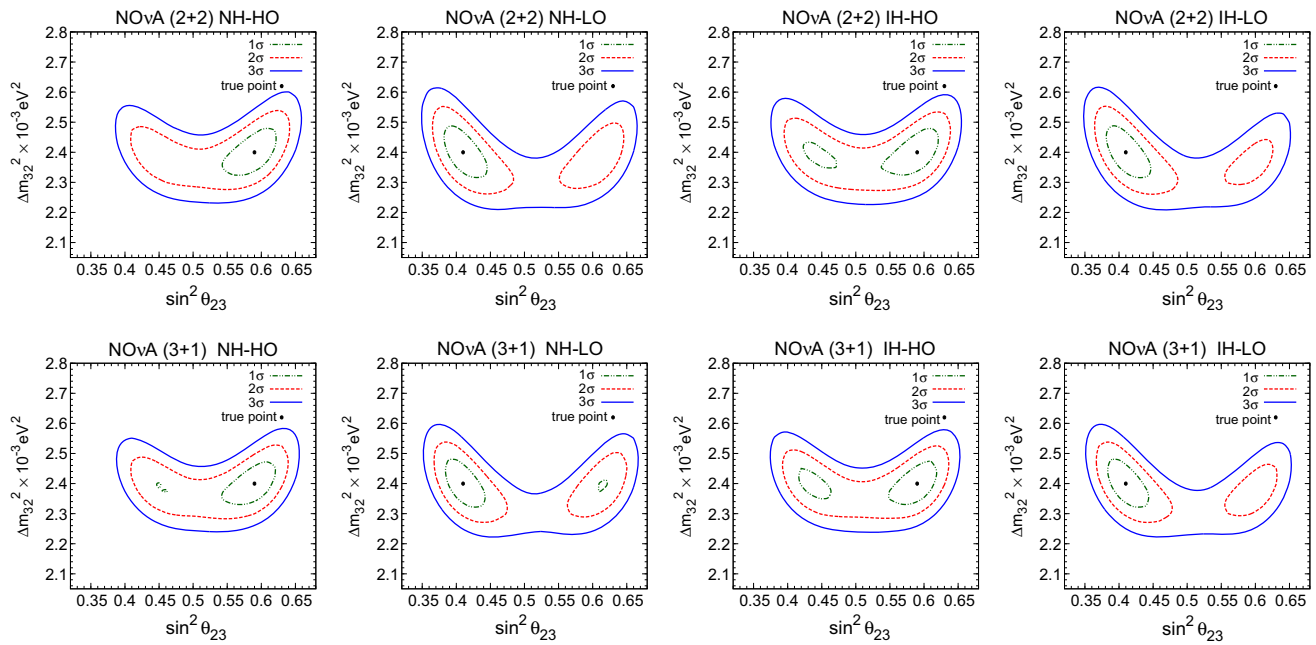


Fig. 6 The 1σ (green), 2σ (red), and 3σ (blue) CL regions for $\sin^2 \theta_{23}$ vs. Δm_{32}^2 with true $\sin^2 \theta_{23} = 0.41$ (0.59) for LO (HO) and true $\delta_{CP} = 0$

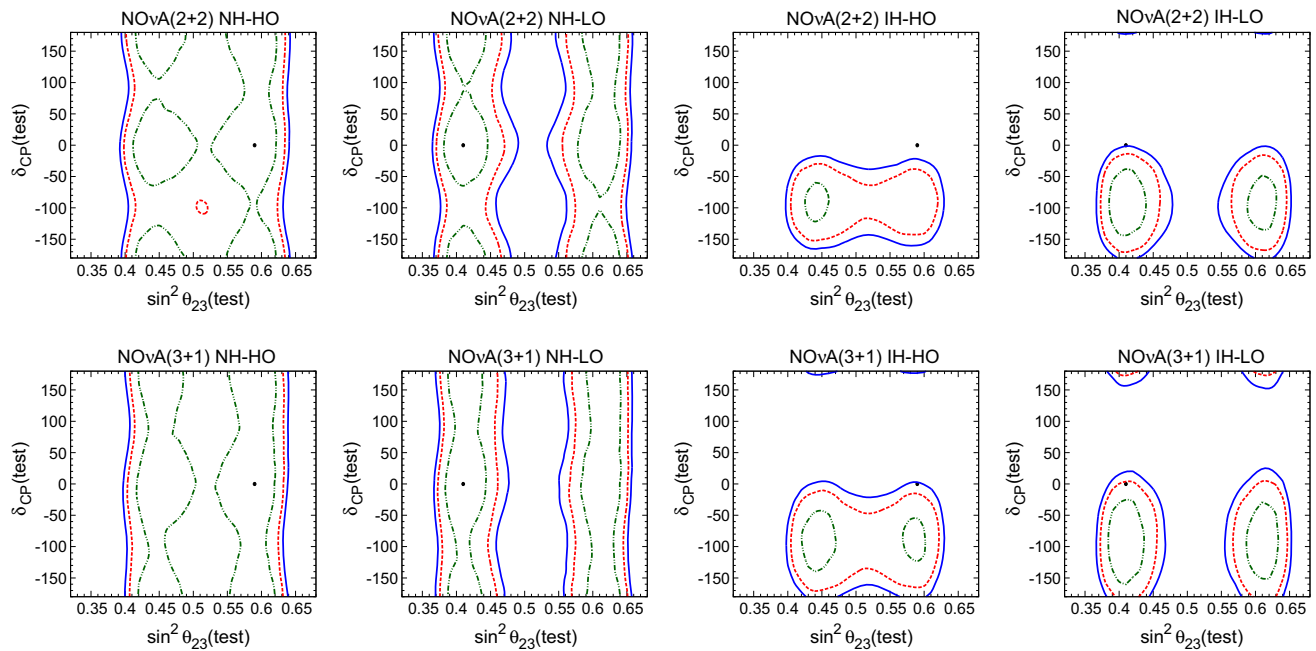


Fig. 7 The 1σ (green), 2σ (red), and 90% (blue) CL regions for $\sin^2 \theta_{23}$ vs. δ_{CP} with true $\sin^2 \theta_{23} = 0.41$ (0.59) for LO (HO) and true $\delta_{CP} = 0$

4.4 Correlation between δ_{CP} and $\sin^2 \theta_{23}$

Another way to understand the degeneracies among the oscillation parameters is by looking at $\sin^2 \theta_{23}$ – δ_{CP} plane. In this section, we show the 1σ , 2σ , and 90% CL regions for $\sin^2 \theta_{23}$ vs. δ_{CP} for both NOνA(2 + 2) and NOνA(3 + 1). Figure 7 shows the CL regions for NOνA with the true $\sin^2 \theta_{23} = 0.41$

(0.59) for LO (HO) and the true $\delta_{CP} = 0$, whereas Fig. 8 corresponds to the true $\delta_{CP} = \pi/2$. Further, the true hierarchy is assumed to be the normal hierarchy and the CL regions are obtained both for the correct hierarchy (NH–LO and NH–HO) and the wrong hierarchy (IH–LO and IH–HO) combinations. The black dots in these figures correspond to the assumed true values. From these figures, we can see that

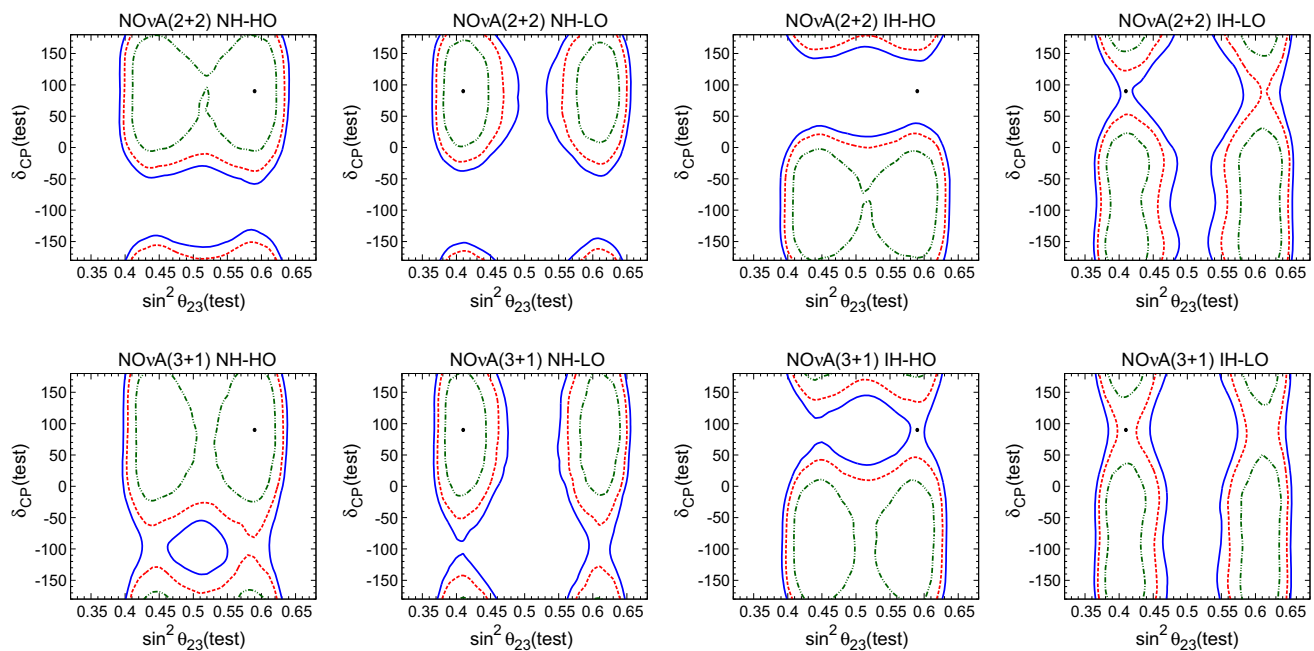


Fig. 8 The 1σ (green), 2σ (red), and 90% (blue) CL regions for $\sin^2\theta_{23}$ vs. δ_{CP} with true $\sin^2\theta_{23} = 0.41(0.59)$ for LO(HO) and true $\delta_{CP} = \pi/2$

$\text{NO}\nu\text{A}(2+2)$ has a better degeneracy discrimination capability than that of $\text{NO}\nu\text{A}(3+1)$.

5 Summary and conclusions

At this point of time, where the $\text{NO}\nu\text{A}$ experiment already started taking data, it is crucial to analyze how to extract the best results from this experiment with shortest time span for a complete understanding of oscillation parameters. In this paper, we discussed the physics potential as well as the role of parameter degeneracies in the determination of the oscillation parameters of the $\text{NO}\nu\text{A}$ experiment with a total of 4 years of runs with $(2\nu + 2\bar{\nu})$ mode. We find that the parameter degeneracy discrimination capability of $\text{NO}\nu\text{A}(2+2)$ is quite good when compared with $\text{NO}\nu\text{A}(3+1)$. Looking at all these results from our analysis, it is strongly urged that after 2 years of neutrino running, $\text{NO}\nu\text{A}$ should run for 2 years in antineutrino mode to provide better information as regards the determination of neutrino mass ordering and the octant of the atmospheric mixing angle.

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